TESTING OF ELECTRICAL MEASURING INSTRUMENTS

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CONTENTS.

1. ELECTRICAL MEASURING INSTRUMENTS.

(*a*) GENERAL.

Electrical measuring instruments may be classified as indicating, integrating, and recording. Indicating instruments give the value of an electrical quantity at the time of observation, or may be so balanced or manipulated as to give such a value. Integrating electrical instruments involve the element of time, as well as the electrical quantity; for example, a watthour meter gives a reading proportional to the product of the average power and the time, or, in other words, to the energy that has passed through it. Recording[1] instruments, properly so called, draw a curve or other graphic record showing some electrical quantity as a function of time.

Electrical instruments may be further classified, according to construction and method of use, into switchboard, portable, and semiportable or laboratory types.

Indicating electrical instruments may be divided into three classes, the first class being capable of service on direct current only, the second on both direct and alternating current, and the third on alternating current only.

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[1] In this connection it should be noted that a wrong use of terms has grown up in regard to the integrating meters generally used for measuring the energy delivered to consumers. The watthour meter, often incorrectly called a "recording wattmeter," is not a recording instrument, nor is it a wattmeter. Some makers appear to have recognized this incorrect use of terms, for they call their meters integrating wattmeters; as the instrument is not a wattmeter, this change does not entirely correct the error. The effect of this mistaken use of terms is to cause confusion when a true recording wattmeter is spoken of. It has seemed necessary to one maker to call his recording wattmeter a "curve-drawing wattmeter," while another maker uses the expression "graphic recording wattmeter." It would be a step in the right direction if meter makers and users would substitute the name "watthour meter" for the incorrect terms now in use.

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(b) Direct-Current Instruments.

While many types of instruments have been devised for the commercial measurement of direct current and voltage, the permanent-magnet, moving-coil instrument has become the standard type for this work. In essential principle this instrument is the same as the d'Arsonval galvanometer. It consists of a light coil free to turn in the field of a fixed permanent magnet. The magnet is usually provided with soft iron pole pieces so shaped as to give a uniform radial field in which the coil moves. The motion of the coil is opposed by a counter force, usually that of two flat spiral springs which also serve to carry the current to and from the coil. Since the deflecting torque is proportional to the product of the (constant) field strength and the current in the coil, and the counter torque of the springs is approximately proportional to the angle through which the coil has turned from the initial position, it follows that the deflections will be approximately proportional to the current strengths; or, as it is commonly expressed, the scale is "uniform" or "proportional."

Since the instrument gives a deflection proportional to the current flowing, it is always, in reality, an ammeter, whether used as such or as a voltmeter. When used as a voltmeter the coil is composed of many turns of fine wire, and a resistance coil is connected in series with it. The value of this series resistance is so chosen that a given maximum voltage, as 150 or 300 volts, will cause the current corresponding to full scale deflection to flow through the coil. The scale may then be marked directly in volts. If small currents are to be measured, they may be passed directly through the moving coil; when the current to be measured exceeds that corresponding to full scale deflection, it becomes necessary to divert a portion of it through a circuit connected in parallel with the coil. By this means it is possible to measure heavy currents of any desired magnitude, the heavy current being passed through a suitable low resistance, called a "shunt," from two points on which small leads run to the instrument. In order to reduce the voltage necessary for full scale deflection in a moving-coil instrument for current measurement, it is customary to wind the moving coil with a much smaller number of turns than in the case of the voltmeter. The wire used is considerably larger. In one well-known instrument made in this country such coils are often wound of one layer of wire in three sections connected in multiple. To assist in reducing the current required for full scale deflection, it is customary to use springs weaker than those used in a voltmeter; as the resistance of these springs becomes appreciable in comparison with the low resistance of the coil, it is necessary to make them of special high-conductivity alloy. A moving-coil instrument so designed for the measurement of current, in connection with a shunt, is called a millivoltmeter, the combination of millivoltmeter and shunt being known as an ammeter. If the millivoltmeter is to be used in connection with any desired shunt, its scale may be calibrated directly in millivolts. If it is to be used in connection with one or more shunts specially made for it, the scale may be marked in amperes. The shunt is sometimes contained within the instrument. In many instances, however, the use of separate shunts is of advantage.

This type of ammeter and voltmeter is made in a great variety of sizes, from the small "watch-case" pocket instrument to the large station model with a scale 3 feet long, the instrument being 3 feet wide and $2\frac{1}{2}$ feet high. It is thus evident that the widest range of practical requirement as to size has been provided for; the same may be said of the current and voltage ranges available. It should be remembered, however, that while high accuracy can not be had in a pocket instrument, the accuracy does not increase indefinitely with the size. It is doubtful whether the use of a pointer over 4 inches in length is worth while, from the standpoint of accuracy. In switchboard instruments which must be read from a distance it is necessary at times to increase the dimensions of the instrument for the sake of legibility. For the

laboratory and testing room the most suitable instrument is the one commonly known as the standard portable, with an index from 3 to 4 inches in length. With these instruments a reading may be made to 0.1 division, or say $\frac{1}{1500}$ of the full scale deflection. With this length of index defects in spring performance may usually be observed. When to this source of uncertainty we add the variations due to changing temperature, stray magnetic field, change of magnets and springs with time, overload, mechanical vibration, or other service conditions, it may readily be seen that a long pointer will magnify the defects of the instrument in the same ratio that it reduces the errors of reading. The question of sources of error is treated in a later paragraph (p. 10).

The variety of sizes, ranges, and types of switchboard instruments is so great that little can be stated in the way of a general rule for the choice of such instruments. One point of special importance, however, in this class of work is the effect of stray magnetic field. The instruments used on switchboards should have shielded movements, and should, as far as possible, be inherently free from error due to stray field. It is further desirable to minimize stray field in the neighborhood of the instruments by care in the arrangement of heavy current conductors.

(*c*) Direct-Current and Alternating-Current Instruments.

Instruments for use on both direct and alternating currents may be divided into four types, namely, **electrodynamometer, electromagnetic, hot-wire,** and **electrostatic.**

Of these four the **electrodynamometer** type is probably the most valuable, all things considered. This instrument depends upon the force exerted by one circuit traversed by a current upon another, or by a portion of a given circuit upon another portion of the same circuit. Instruments of this type usually contain one or more fixed coils which set up a magnetic field directly proportional to the strength of the current flowing through them. Within this field is arranged a moving coil or system of coils through which current may be passed. If the two sets of coils are connected in series, the torque exerted upon the moving system, for a given relative position of the coil systems, is proportional to the square of the current strength, and is not dependent upon the direction of the current. Such an instrument constitutes an ammeter which is equally correct on direct current and on alternating or pulsating current of any frequency[2] or wave form. The value of this type of instrument lies very largely in this inherent accuracy on these various kinds of current. Since the fundamental electrical standards and precision methods of testing involve direct current only, the electrodynamometer instrument, calibrated on direct current, may be used as a precision instrument for alternating current. The ammeter of this type, just referred to, has certain limitations. If the current is carried into and out of the moving coil by the usual spiral springs, only small currents may be used without injury to the springs. In the Siemens electrodynamometer, one of the earliest practical instruments of this type, the current is taken into and out of the moving coil by mercury cups; in the Kelvin balance the axis about which the moving system turns is horizontal, and ligaments of fine wire are used as supports and conductors. Both of these instruments have done good service in their time, but they are slow and inconvenient to use and require that the current to be measured be quite steady. The Kelvin balances change appreciably due to heating, when kept in circuit for any length of time, and have frequency errors which are greater the larger the

[2] This assumes that no change takes place in the distribution of the current over the cross section of the wire; with thick wires and high frequencies the current will tend to flow near the surface of the wire, and the reading of the instrument for a given current will vary to a certain extent with the frequency.

It is also assumed that no masses of metal are near the coils; if such masses are in position to have eddy currents set up in them by the action of the coils, errors will result.

ampere capacity of the balance. In order to provide a portable and easily operated ammeter of the electrodynamometer type, several European makers arrange the fixed coils and the moving coils in parallel, so that the latter carry only a small part of the current to be measured. In order to avoid differences in the division of the current, due to inductance, the time-constants of the two circuits are made small and as nearly equal as possible, by adding noninductive resistance to each coil. As this added resistance is of manganin, the temperature coefficient of each circuit is reduced; it should be noted, however, that only *differences* in the temperatures of the two circuits will introduce error. These instruments are suited for use in the laboratory, for checking alternating-current ammeters of the electromagnetic and other types which can not be accurately calibrated with direct current. For this purpose the electrodynamometer ammeter is calibrated with direct current, using a potentiometer; readings are taken for both directions of current through the ammeter, and the mean of the two readings is used. The mean of these readings eliminates the influence of the earth's field, and the ammeter may now be used on alternating current of any commercial frequency with an error which is practically negligible in well-made instruments. The saving in time by using such instruments instead of Kelvin balances is very great, and the apparatus is less expensive.

The electrodynamometer voltmeter has fixed and moving coils of moderately fine wire, connected in series with each other and with a noninductive resistance of low temperature coefficient. This latter resistance (for usual commercial voltages) brings the time-constant (ratio of inductance to resistance) down to a small value, and hence well-made voltmeters of this type, calibrated on direct current, show practically negligible errors on commercial alternating-current circuits. These instruments, if properly made, are thus suitable for checking other working instruments. In this connection it should be noted that alternating-current voltmeters require considerably larger currents than the moving-coil voltmeter for direct currents. A consequence is that more heat is produced in the series resistance; if no provision is made for ventilation this heat accumulates, raising the temperature of the springs and other parts of the instrument and affecting the readings. A voltmeter of this form for precision work should have the series resistance ventilated, and separated from the dynamometer system.

If the fixed coils of an electrodynamometer are made of thick wire, and are connected in series with a load, while the moving coils of fine wire are connected (with a series resistance as in a voltmeter) across the line supplying the load, the resulting instrument will measure the power expended upon the load, and constitutes a wattmeter. Instruments of this kind afford a very convenient method of measuring the power taken by alternating-current lamps, motors, etc., and in testing alternating-current watthour meters. With these wattmeters, as usually constructed, it is necessary to take the mean of two readings, when using direct current, in order to eliminate the effect of the earth's field. This effect varies with the position of the moving coil in the earth's field, and a position of this coil may be found such that the effect disappears.

By modifying the arrangement of the circuits, the wattmeter may be arranged to measure the power factor, or phase angle between current and voltage.

Instruments of the **electromagnetic** type depend upon the action of a coil traversed by a current upon one or more pieces of soft iron. These instruments are also designated as "moving-iron" and "soft-iron" type. Instruments of this general type have been employed for many years. They have the advantages of simplicity and low cost. At one time they were constructed with heavy iron rods, which were drawn into solenoids; it is now generally recognized that this is a very poor design. The quantity of iron should be very small, and the length of the path of the magnetic lines in the iron should be small compared with the length of path in air. In addition, it is important to have iron of very good magnetic quality, to reduce errors due to hysteresis and eddy currents; it is also necessary to avoid magnetizing the iron too close to

saturation. Well-made instruments of this type are now available at moderate prices. The ammeters are very slightly affected by even large frequency changes; the voltmeters, on account of their relatively high time-constant, are more affected than the ammeters. The error in the voltmeter is not large over the commercial range of frequencies, and may be computed, for unusual frequencies, from the measured values of resistance and inductance. A valuable feature of these instruments is their very small temperature coefficient. These ammeters and voltmeters are well suited for commercial measurements on alternating-current circuits, and for direct current when only approximate results (within 2 or 3 per cent) are required. When intended for use on alternating-current circuits they should be calibrated with alternating current, using suitable transfer instruments which may be checked with direct-current standards. The electromagnetic voltmeter or ammeter can not be checked accurately on direct current, as even the mean of reversed readings does not give an accurate test of the performance on alternating current.[3]

The results of Benischke [4] are sometimes quoted as showing that electromagnetic ammeters and voltmeters, though practically independent of frequency variations, are seriously affected by such departures from the sine wave form as are met in practice. While his results are doubtless correct for the old and badly designed electromagnetic instruments he used, modern well-made instruments show only a few tenths of 1 per cent change for as large variations in wave form as would probably be encountered in practice, except in the case of very badly designed alternators.

Instruments of the **hot-wire** type depend upon the expansion of a wire which is heated by the passage of a current. In one of the earliest of hot-wire voltmeters (the Cardew) a fine platinum-silver wire was used, of such a length (several yards) that it could be connected across the usual 110-volt circuit without any series resistance. The necessity of accommodating such a length of wire caused the instrument to be bulky; it is no longer in use. The more modern instruments of the hot-wire type have a working wire 6 or 8 inches in length; this working wire is quite fine in a voltmeter, and a series resistance is provided. In the hot-wire ammeter the working wire is of larger diameter, and is connected with several sections in parallel, to reduce the required drop in the shunt. The hot-wire instrument is not used in this country to any great extent in practical work; its defects are relatively large consumption of power, uncertainty of zero, errors due to change of surrounding temperature and to heating when left in circuit. As the working wire must be run at a fairly elevated temperature to give proper sensibility, it is easily damaged by sudden overloads, which would do little or no damage to other forms, except the possible bending of a pointer. The good points of the hot-wire instrument, which cause it to be still used for certain classes of work, are its independence of frequency, wave form, and stray magnetic fields; the fact that it may be calibrated on direct current, and that shunts may be used with the ammeter for alternating current. For use in the laboratory with unusual frequencies or wave forms, and where facilities are at hand for ready calibration on direct current, this form of instrument possesses some marked advantages. It should be noted, however, that for very high frequencies, such as are common in wireless telegraphy,

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[3] In this connection it should be mentioned that one maker in this country constructs a soft-iron ammeter in a style of case identical with that used with his electrodynamometer wattmeter, both instruments being operated by a torsion head. This soft-iron ammeter has consequently been assumed by some users to be of the electrodynamometer type, and hence capable of accurate use on alternating current after test with reversed direct current. Other makers supply electrodynamometer instruments and soft-iron instruments in the same form of case, with nothing to indicate the difference. It would be an improvement if all instruments were plainly marked in this respect. In case of uncertainty as to the principle of operation of an instrument, the prospective purchaser would do well to obtain this information from the maker.

[4] Benischke, Elektrotechnische Zeitschrift, vol. 22, p. 301; 1901.

shunted hot-wire ammeters are by no means reliable, as for such frequencies the effective resistance of the shunt is considerably greater than for direct current, and the time-constants of shunt and instrument, which ought to be equal, may be very different. For such extreme frequencies the only reliable method would be to construct the hot-wire instrument so that the use of a shunt is unnecessary, the whole current passing through the working wire, which should be such that the effective resistance for the frequency used will be practically equal to the direct-current resistance.

Instruments of the **electrostatic** type depend upon the attraction of oppositely charged bodies, and repulsion of similarly charged ones. As these forces are relatively small, such instruments can not well be made as ammeters, and in fact it is difficult to construct satisfactory voltmeters on this principle for the ordinary 110-volt range. The great advantage of this type of voltmeter is that it takes no current, when used on direct-current circuits, and an extremely small current when used on alternating-current circuits. Like the hot-wire instrument, it is not affected by frequency changes, wave form, or stray magnetic field. It has the defect of small ratio of torque to weight of moving parts, so that frictional errors are hard to avoid. For this reason, low-range instruments of this type are frequently made with a suspension strip or wire in place of pivots. While these instruments are used abroad to some extent, in this country they find little use except in the laboratory; an exception is the electrostatic ground detector, which is really a voltmeter. For very high voltages the electrostatic voltmeter has some marked advantages over other types, if the use of potential transformers is not considered. Wattmeters may be constructed on the electrostatic principle, but the practical application of such instruments seems improbable.

(*d*) Alternating-Current Instruments.

Instruments operating only on alternating current depend upon the interaction of inducing and induced currents, and are usually described as induction instruments. The usual form contains a laminated iron core surrounded by one or more coils of wire; an alternating magnetic flux is set up in the air gap of this core when current flows through the coils. Provision is made for securing the effect of a rotating field, either by having more than one group of coils, the currents in them differing in phase, or one coil may be used, with fixed copper plates or bands, in which induced currents are set up; the resultant action of the flux due to the coil and that due to the induced currents in the fixed copper pieces gives the effect of a rotating field. In this field is pivoted a light disk or drum, usually of aluminum, which tends to rotate with the rotating field. If an indicating instrument is desired, the motion of the disk is opposed by a spring or other suitable counter force; an integrating meter is provided with drag magnets and a dial or register to read the total quantity that has passed through the meter. An inherent defect of this type of meter is that it tends to vary greatly in its readings with change of frequency; in some forms it has also large temperature errors. Much skill and ingenuity have been devoted to the improvement of the induction instrument, and the induction watthour meter in particular has been developed into a reliable commercial instrument, having the great advantages of absence of commutator and brushes, and a very light moving element.

Portable induction indicating instruments have been used to a considerable extent, their inherent defects being partially compensated for by their practical advantages. They have a nearly closed magnetic circuit, and have fairly strong working fields; they are thus not sensitive to external stray field. The moving element is simple and strong, has no windings, and hence requires no provision for leading current in and out. The scales are long, it being possible to make them cover 300°, or even more; this advantage, however, is often overestimated. Such instruments may be used for commercial testing on definite frequencies, after calibration under conditions as nearly as possible like those under which they are used. They are not suitable for general service in the laboratory, where a wider range of frequencies is met with;

for commercial use they should be checked by comparison with proper standards, for important work. This refers to the more modern instruments; some of the older types can hardly be called measuring instruments, as they vary so greatly with changes of frequency and of temperature. It is, of course, impossible to use induction instruments on direct current.

(*e*) Integrating Instruments.

Integrating meters, as used in this country, may be divided into chemical meters and motor meters; by far the greater number of meters in use are of the latter type. In the **chemical meter,** the passage of a direct current through an electrolyte decomposes a chemical compound, and gives a measure of the ampere-hours. The Edison chemical meter employed two zinc plates in a solution of zinc sulphate, the bottle containing the plates being placed in the meter at the beginning of the month and replaced by a similar bottle at the end of the month. One of the zinc plates (the anode) was carefully weighed before and after this term of service, and from the loss in weight the amount of the bill was calculated. To pass the whole current through the bottle would be impracticable, on account of the large size of the plates that would be needed; the bottle was therefore put in a shunt circuit, and only about one one-thousandth part of the main current passed through it. This shunting caused a large part of the theoretical accuracy and reliability of the electrolytic meter to disappear; the voltage causing electrolysis being very low at light load, any polarization in the cell, or abnormal resistance due to oxidation of the plates, would make the meter under register. This meter was at one time used to a considerable extent, but is now of historical interest only.

The electrolysis of liquids has also been used, and is so used to a small extent at this time. Such meters have many drawbacks, and their only evident advantages would seem to be their simplicity and low first cost. They are, of course, ampere-hour meters, though sometimes incorrectly marked as "wattmeters."

The **motor meter** has been very highly developed, and has found a wide application. For direct-current work it is usual to employ a meter which is essentially the same as the well-known Thomson watthour meter brought out about twenty years ago. This meter contains a small direct-current motor free from iron; the line current passes through the fixed field windings, while the armature is wound with fine wire and connected (through a series resistance) across the line. On the shaft of the motor is a disk of copper or aluminum, rotating between the poles of permanent magnets; the upper end of the shaft has a worm which engages the first wheel of the register. The direct-current motor meter of to-day differs from the original only in details and refinements of construction. These have reduced the weight of the moving element and increased the torque; both of these improvements tend to make the meter more accurate on light loads, and more reliable in service. The power required in the armature circuit has also been reduced; while this is small for a single meter, it becomes an important matter for large installations, as energy is being consumed as long as the voltage is on the line.

In recent years a direct-current meter has been put on the market in this country, which eliminates the commutator and reduces the effective weight of the moving system very considerably. This meter has a copper disk submerged in mercury; the line current enters the mercury chamber, flows diametrically across the disk and out at the other side. A laminated iron core, surrounded by a winding of fine wire connected across the line, provides a magnetic field nearly proportional to the line voltage. The disk rotates, due to the interaction of the line current in it and the field due to the shunt coil.

Recently an ampere-hour meter has been devised, which is similar to the watthour meter just described, but has a strong permanent magnet to provide the field through the copper disk.

For alternating-current work the **induction watthour meter** has many advantages over the type using commutator and brushes. The loss in the potential circuit and that in the

series coil of a good induction meter are very small. The moving system is light in proportion to the torque, and in those designs using nearly closed magnetic circuits the effect of local stray field is usually small. The Thomson type of direct-current motor meter may be used on alternating-current circuits, with an error which is due to the inductance of the armature circuit and is smaller, the lower the frequency and the more nearly the load has unity power factor; for very low power factors the percentage error will be considerable. To avoid this error, a noninductive resistance may be connected as a shunt to the series field. This resistance will take a component of the line current which leads the phase of the other component in the series coil. This resistance is adjusted until the current in the series coil lags behind the line current by an angle equal to the angle of lag of the voltage circuit. Such a meter will read correctly at the given frequency for all power factors.

In the mercury meter above referred to, the high inductance of the potential circuit (of the direct-current type) would greatly cut down the current, if it were attempted to use this meter on an alternating circuit; further, the current would lag considerably behind the voltage, and hence the torque of the meter would not be proportional to the power. To overcome this difficulty, in the alternating-current type the line voltage is applied to the primary of a small transformer located inside the meter. The secondary coil of this transformer sends a relatively large current at very low voltage through the mercury chamber and copper disk. The series coil of the meter is now wound on the iron core and provides a field which is approximately proportional to the current in the line. It will be seen that in this alternating-current meter the relative positions of series and potential current are the reverse of those in the corresponding direct-current meter.

In order to facilitate the testing of electric meters in the premises of consumers, a number of **portable watthour meters** have been devised. These are sometimes called "rotating standards;" they are substantially the same in construction as the service meters, but have arrangements for varying the current range, by having a separate coil for each range, or a stranded coil whose sections may be grouped in various ways, or by a combination of these methods. The style of mounting is such as to adapt them for portable use, and the dials are such as to enable a close reading to be made for very short runs. These meters are constructed on the induction principle for alternating current; this gives a satisfactory instrument for commercial work on a definite frequency. Direct-current meters, on account of the use of commutator and brushes, and the much higher drop in the field coils, are not so satisfactory as the former. In either case, the test meter should be considered as a secondary instrument, liable to change in use, and it should be frequently checked by reliable standard instruments.

The report of the meter committee of the National Electric Light Association for 1909 contains considerable detailed information in regard to watthour meters.

(*f*) Recording Instruments.

Recording electrical instruments make a graphic record of the varying values of current, voltage, power, or other characteristics of the circuit to which they are connected. They may be classified as **direct-acting** and as **relay** instruments; in the former the moving element of the meter makes the record, while in the latter the moving element operates relay contacts and thus brings into action a separate device for making the record. A difficulty in the former case is the friction of the pen on the paper; this difficulty has been attacked in various ways. In one form of instrument the operating system is made larger and more power is taken by it, thus giving a large torque; the friction of the pen on the paper is thus rendered small in comparison. This larger power must frequently be taken from the secondary circuits of instrument transformers, and hence care is necessary to have these transformers large enough for the

service; otherwise errors of transformation will arise. In another instrument a tracing point is carried on the moving index, this point being out of contact with the paper, except at frequent intervals when a bar is depressed, bringing the point down and making a dot on the paper. By arranging the apparatus so as to make these dots frequently, an approximation to a continuous curve is made. The advantage of this method lies in the fact that the index is free to take up its proper position between depressions; the moving system may be small and light, and require very little power. This form of recorder is used in pyrometric measurements, in connection with thermoelements. The attempt has also been made to eliminate friction by causing an electric spark to jump from a point on the moving index to the paper; this method has apparently found little use in practice.

Recording meters on the relay principle have the advantage of small power required by the instrument, thus making unnecessary the use of special instrument transformers for alternating-current work. This advantage is secured at the expense of greater complication, and the use of contacts, which require attention.

As a rule, recording instruments are not capable of giving precision results. They should be checked in position, using portable instruments whose corrections are known. The same is true of watthour meters, especially large meters on switchboards. These should be tested in position, subject to working conditions of stray field, temperature, etc.

(*g*) Accessory Apparatus, Including Instrument Transformers.

In addition to the instruments briefly described above, reference should be made to some important accessory apparatus. Mention has already been made of the external shunts which enable a millivoltmeter to be used as an ammeter for any desired current range above that of the millivoltmeter alone. The series resistance of a voltmeter for one or more ranges is usually built in as a part of the instrument. When higher voltages than the maximum thus provided for are to be measured, external series resistance boxes, called **multipliers,** are used to extend the range. These are used with alternating voltmeters, so long as the voltage is not too high; above 600 volts, as a rule, the use of a multiplier would be discontinued. In its place is used a small transformer whose primary coil is wound for the maximum line voltage to be measured, while the secondary voltage (usually 100 to 110 for normal working line voltage on the primary) is applied to the voltmeter. Such **potential transformers** are usually wound for some convenient integral value of the ratio of primary applied voltage to secondary terminal voltage. This arrangement has the great advantage of insulating the voltmeter from the high voltage of the line. In case the latter is 1,000 volts or more, this is a very important point in connection with safety to the operator.

Alternating-current ammeters do not, as a rule, lend themselves readily to operation from shunts; further, the same necessity frequently exists in this case, as for the voltmeters, of insulating the instrument from the line voltage. The **current transformer**[5] accomplishes both functions, and when well designed, constructed of proper materials, and not required to operate too many instruments, is a very satisfactory piece of apparatus. Care should be taken not to connect more instruments than the transformer is designed to operate, especially when one of the instruments is a wattmeter or a watthour meter. In the operation of these latter instruments by current transformers, two sources of error arise; first, the ratio of transformation varies with the primary current, the rate of change of the ratio (for a given transformer) being greater the smaller this current; second, the secondary current is not exactly in opposition to the primary current, and this deviation from opposition (usually referred to as the

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[5] Often referred to as "series transformer," and occasionally as "series converter;" the last expression should be discarded.

"phase angle") will usually increase as the load decreases. The light-load performance of the transformer will of course depend in the first place upon its design and the quality of the materials used in its construction, but for a given transformer the general performance will be better the smaller the load of instruments it is required to operate; that is, the lower the resistance and reactance of the secondary circuit. As both ratio and phase angle errors affect the reading of a wattmeter,[6] care should be taken that the series transformer used with the wattmeter is of proper design and capacity and that it is not overloaded with instruments.[7]

The secondary circuit of a series transformer should never be opened while current is passing through the primary, not only on account of the rise of voltage at the secondary terminals, which may become dangerously high, but also because both the ratio and the phase angle will be changed. Under such conditions the flux in the iron rises to abnormal values; the iron is not left in a magnetically neutral condition, so that both the magnetizing current and the core loss are increased, thus changing the constants of the transformer. For the same reason, direct current should never be passed through the transformer. In case an open circuit accidentally does occur, the effect may be removed by demagnetizing the core. This may be done by passing full-load alternating current through the primary while the secondary circuit is open, and gradually decreasing the current to zero.[8]

An overload of instruments on the secondary circuit should be avoided in the use of potential transformers, but the question of change of ratio at low voltages does not arise in practice, as potential transformers usually operate close to some standard value of line voltage. In well-made potential transformers the phase angle is negligible, for practical purposes, as long as the current taken from the secondary is not too great. Care should be taken not to exceed the rated capacity of the secondary circuit; if the instruments used are inductive, the volt-amperes they require may be counted as so many watts in estimating the load on the transformer secondary.

(*h*) Sources of Error.

An important matter in connection with the use of electrical instruments is the question of sources of error and the best means of securing a required degree of accuracy from a given set of instruments. It may be said in the beginning that in very many cases the user underestimates the errors and overestimates the accuracy of the result. This is partly due, in many cases, to the lack of means for checking the results obtained; as there is no check, inaccurate results are passed without suspicion of their inaccuracy, and the maker's representations as to instrument accuracy, which are sometimes much exaggerated,[9] are accepted as correct for an unlimited time after the maker's test and for all conditions of use. Portable instruments are often used in places subject to strong stray field or extreme temperatures; subsequent comparison with other instruments in the testing room may show that the working instruments have small errors, while their performance under the unfavorable working conditions may have been 5 per cent or more in error.

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[6] Nies, Polyphase Metering, Trans. American Institute of Electrical Engineers, vol. 24, p. 165; 1905. L. T. Robinson, Electrical Measurements on Circuits requiring Current and Potential Transformers, Trans. American Institute of Electrical Engineers, vol. 28; July, 1909.

[7] A good practical article on "Measurements involving the use of Series Transformers" is given by H. B. Taylor, in Electric Journal, vol. 4, p. 234; 1907.

[8] A full discussion of this effect will soon appear in the Bulletin of the Bureau of Standards.

[9] A foreign maker, for instance, states that the *form* in which his permanent magnets are made gives "absolute constancy," as well as independence of stray fields. Such expressions as "absolutely accurate" and "absolutely permanent," when applied to instruments containing changeable elements like magnets and springs, are to be deplored as showing either ignorance of the facts, on one hand, or intent to deceive the purchaser, on the other. Fortunately, such expressions are rarely used at this time, as reputable makers are becoming more careful and conservative in their statements.

Under the head of inherent errors may be noted first those due to the effect of **change of temperature** on the various parts of the instrument. Taking, for example, a voltmeter of the permanent-magnet, moving-coil type; if it reads correctly at a given point at a certain temperature, it will in general show a small error at any other temperature. The effect of an increase of temperature above the normal is to decrease the strength of the magnet, which tends to reduce the reading for a given voltage. On the other hand, this increase of temperature weakens the springs, and hence these two effects tend to balance each other. The temperature coefficient of the springs is about 0.04 per cent per degree C; that of the magnet is not so definite. The resultant temperature coefficient of the instrument, used as an ammeter with the whole current flowing through the coil, is quite small as a rule.[10] The question of making such an instrument practically free from temperature error, when used as a voltmeter, is then relatively simple, as it is only necessary to have a low value of the resistance temperature coefficient of the circuit. Such a moving-coil voltmeter will have a copper coil requiring, say, 0.5 volt at the coil terminals for full scale deflection. If no external resistance were used in series with the coil, the instrument would have a large temperature coefficient (about 0.4 per cent per degree C) as a voltmeter. If we add an external resistance of manganin, such that the total resistance is now ten times the coil resistance, this temperature coefficient will be reduced to about 0.04 per cent per degree; the range of the voltmeter is now 0 to 5 volts. For a range of 50 volts the temperature coefficient will be still less. It is thus seen that where such a voltmeter has low ranges and high ranges, a larger temperature coefficient is to be expected on the lower ranges. If it is necessary to construct a low-range voltmeter of low temperature coefficient, this can be done by using a moving coil of fewer turns and lower resistance. Other things being equal, this second coil, with sufficient manganin wire to give the same volt range, will have a smaller ratio of copper resistance to total resistance, and hence the temperature coefficient will be reduced.

In the preceding it has been assumed that temperatures within the instrument were the same. If no source of heat existed in the instrument, and the only changes of temperature were due to changing room temperature, this would be very nearly the case. Most instruments, however, contain sources of heat, usually coils of wire through which currents flow. Unequal heating is therefore possible, and some error will result from this cause. When, as in alternating-current voltmeters and wattmeters, a large portion of the resistance is so-called "dead" resistance in series with the working element, this heat-producing resistance should be partitioned off from the working system, and properly ventilated. Neglect of this precaution usually results in an instrument which can not be left in circuit for any appreciable time without error.

An important instance of large errors through unequal heating within the instrument is afforded by the direct-current permanent-magnet moving-coil **ammeter with internal copper shunt.** In these instruments the moving coil, of copper, is connected to the terminals of a copper shunt within the instrument case. As the temperature coefficient of the moving coil used alone as an ammeter is quite small, and as changes of *room* temperature will not alter the relative distribution of the current between moving coil and shunt, such an instrument would seem at first sight to be almost an ideal one. In the smaller sizes, the performance is quite good. In large sizes (say from 300 to 500 amperes), these instruments change very rapidly after closing the circuit, and are not suitable for any but rough work. In general, it may be said that up to about 25 amperes, well-made instruments of this type will give fairly good service; above that they should not be used for careful work. The use of manganin for precision ammeter shunts is now recognized as the best practice. For heavy currents, the shunt and millivoltmeter should be separate.

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[10] Heinrich, Handbuch der Elektrotechnik, vol. 2, pt. 5, p. 12.

On account of the desirability, for commercial reasons, of keeping down the size and weight of ammeter shunts, as well as the waste of power in them, **millivoltmeters** are designed to give full scale reading for very low voltages; the design of winding and spring for this object having already been mentioned. A very common value of this voltage is 50 millivolts, where the instruments are intended for switchboard use. As the shunts are usually made of a material of low temperature coefficient, while the millivoltmeter circuit consists largely of copper, the error due to varying room temperature may be considerable. This is ordinarily not a matter of great moment, as switchboard ammeters serve mainly as indicators to guide in the operation of a plant, to prevent overloading of generators, motors, or feeders. However, when ammeters are used for precision work in the laboratory, or in the testing of direct-current watthour meters, the temperature errors above referred to become very objectionable. To remedy this, most makers manufacture a line of millivoltmeters which have added to the copper coil a manganin resistance which is from, say, four to nine times the copper resistance. This cuts down the temperature coefficient of the instrument, but requires a higher drop in the shunt—namely, from 150 to 200 millivolts for full load. When these shunts are properly made, the resulting combination of millivoltmeter and shunt makes a satisfactory ammeter.[11]

In connection with the question of errors in millivoltmeters, the matter of proper construction of **ammeter shunts** is important. Ordinary "station shunts" will show appreciable errors due to thermoelectric effect; such shunts should not be used for careful work. The design of the terminal blocks, into which the resistance metal is soldered, is often defective, due in part to the small space allowed for shunts in switchboard work. Aside from the errors due to heating, changes of several per cent in the resistance are caused by changes in the method of bolting on the copper bar to the shunt. To overcome this difficulty, the terminal blocks should be made longer, so as to make the lines of current-flow more nearly parallel at the junction of terminal and resistance metal, near which junction the potential terminals should be located. The same result may be attained by constricting the section of the terminal block considerably between the current terminal and the potential terminal.

Errors due to thermoelectric effect may be observed by allowing the current to flow until the shunt has assumed working temperature; on breaking the circuit, the millivoltmeter will show a small current flowing under the action of thermal electromotive forces; this may be distinguished from zero shift by opening the millivoltmeter circuit.

For precision ammeter shunts the most satisfactory material is manganin,[12] and the best makers are adopting it in spite of some additional trouble involved in the manufacture of the shunts.

In the electromagnetic (soft-iron) ammeter, with spring control, an increase of temperature lowers the permeability of the iron, but also reduces the strength of the spring by nearly the same amount; hence these ammeters are very nearly independent of ordinary temperature changes. In the electrodynamometer instrument, the only element of importance, in respect to temperature coefficient, is the controlling spring; as there is nothing of any consequence to balance it, such instruments will read too low at temperatures below that at which they are correct, the temperature correction being about 0.04 per cent per degree C. This assumes that potential or shunt circuits contain so small a percentage of copper that their change of resistance with temperature does not sensibly affect the result. For ordinary voltage ranges this is the case.

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[11] It would seem possible, by modifying the mechanical and electrical design of present millivoltmeters, to produce millivoltmeters for 50 millivolts range, which should be practically independent of temperature changes. It is to be hoped that such instruments will soon be available.

[12] Substitutes for manganin have been proposed, but manganin is the one material shown to be satisfactory by years of experience.

In the soft-iron voltmeter the temperature coefficient depends mainly upon the ratio of the resistance of the copper coil to the total resistance of the instrument. This ratio is a question of design, depending upon the range of the instrument and the amount of power spent in it. The temperature coefficient of well-made voltmeters of this type, for the usual commercial voltages, is quite small, and for practical work need not be taken into account, except in extreme cases.

Errors due to changes of room temperature are usually only temporary, unless the instrument has been subjected to very abnormal temperatures. Another source of error is **change with time and use.** In spite of the labor which has been expended on the question of making permanent magnets, individual magnets of the best makes will occasionally show changes with time. When the instrument is new, the magnet may increase in strength; later it is more likely to decrease. Controlling springs also show slight changes with time. If magnet and springs weaken to the same extent in a direct-current instrument, the accuracy is unaffected. Where direct-current instruments are used in the neighborhood of dynamos or motors, or in other locations subject to strong **stray field** (for example, near heavy conductors), their indications will be considerably affected at the time of use, and in addition, permanent change of the magnets may occur. Switchboard instruments are liable to exposure to stray fields, and should be shielded against them. The iron case very generally used for such instruments affords considerable protection, but in addition, it is recommended that heavy currents be kept well away from the instruments, and as a further precaution, important instruments (watthour meters and voltmeters, for example) should be checked in position, under working conditions. Care must be taken that the portable instruments used in this checking are in a location not exposed to stray field; if this is impossible, the mean of two readings should be taken; for the second reading the instrument is turned 180° from its first position.

Under the head of **inherent errors** of a mechanical nature may be mentioned the friction of pivots, defective performance of springs, error of marking the scale, and lack of balance of the moving coil. The friction of pivots should not be noticeable in a good instrument, unless it is old or has been roughly handled. Good performance in this respect requires not only good workmanship in the pivots and jewels, but also good design. It is evident that friction can not be entirely done away with, and hence the problem is to have a spring strong enough to cause the coil to take up its proper position within the error of reading the position of the pointer on the scale. According to one writer,[13] the **torque** for full scale deflection, expressed in gram-centimeters, should not be less than one-sixth the **weight** of the coil in grams; this weight includes that of springs, index, etc. Heinrich[14] gives a minimum value considerably lower, namely, one-twentieth. In both of these cases a deflection of approximately 90° is assumed, this being very nearly the full scale deflection for most direct-current instruments. The above ratios are for portable instruments for everyday service, and may be departed from in special cases, as for example, in pivoted galvanometers of high sensibility, for laboratory use. It is desirable, in all electrical measuring instruments, to keep the ratio of torque to weight as high as possible. It should be noted that an instrument with a very high torque may really be a poor instrument, if the high torque is obtained by using an excessively heavy moving system.

Suppose that the index of an indicating instrument stands exactly at zero with no current flowing, after a considerable interval (say a day or two) of rest. If current or voltage be applied so as to give the full scale deflection, which is maintained for a short time only, then on breaking the circuit the needle will usually return to zero, within the limit of reading. If we maintain full scale deflection for an hour we shall probably find that on breaking the circuit the index

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[13] Janus, Elektrotechnische Zeitschrift, vol. 26, p. 560; 1905.

[14] Heinrich, Handbuch der Elektrotechnik, vol. 2, pt. 5, p. 14.

does not return exactly to zero; if the full scale deflection lasts several hours the discrepancy will be still greater. The **zero shift** is only temporary, and gradually disappears. The amount of this shift varies in different classes of instruments, and in different individuals of the same class. In first-class voltmeters it should be just noticeable; in millivoltmeters, as a rule, it is considerably greater, although occasionally a millivoltmeter will show a very good performance in this respect. The effect of zero shift upon the reading is greatest when an instrument is used for a small deflection soon after it has sustained a large deflection for a considerable time. The reason for the poorer performance of millivoltmeters lies in the necessity of using springs which approach pure copper in electrical qualities; this causes the mechanical properties also to approach those of copper. For the voltmeters no such limitation exists, and the springs may be made of the bronze which has the most suitable mechanical qualities, regardless of its specific resistance. The zero performance of a spring depends on its design as well; it is evident that an elastic limit exists for any spring, and that the thickness and length of the spring [15] will determine this limit for springs of a given material.

It has often been assumed that the torque of a spiral spring is exactly proportional to the angle of twist; in other words, that the spring obeys Hooke's law accurately. Hence, in testing instruments such as the Siemens dynamometer, the "constant" of the instrument was determined for one value of current, and assumed to hold for any other value; or it was taken as the mean of several determinations with different currents. This assumption is incorrect, and may lead to errors of 1 per cent or more.[16] In the ordinary direct-reading instrument this variation does not appear if the scale is properly graduated. However, if by accident the spring should be thrown out of its original shape, the scale will no longer be correct, even though by shifting the spring holder the index be brought back to zero.

At one time instrument scales were engraved or printed, on the assumption of a particular law; the instrument was then adjusted by trial to make it fit the scale as closely as possible. While this is probably done at the present time for instruments of lower grades, it is recognized that a good instrument should have a scale graduated to fit it. It is not necessary, of course, to determine every scale division by test, especially in direct-current instruments with nearly uniform scales. It is usually considered sufficient to determine say ten or fifteen points by actual test; the intermediate points are filled in, sometimes by hand, preferably by a mechanical method. While for ordinary purposes it is sufficient to check an instrument at, say, five points, for the most careful work this is not sufficient, and points much closer together should be taken. It has been shown [17] that the simple removal and replacement of the pole pieces of a direct-current instrument—in fact, even the tightening of the screws that hold the pole pieces—will affect the distribution of the magnetic flux so that a scale which fitted the instrument before the operation will now show appreciable errors. It may be seen from this, and the fact above noted in regard to deformations of the spring, that any mechanical change, adjustment, or accident to an instrument should be followed by a test. As to initial **accuracy of scale,** some makers claim to make their portable direct-current instruments correct to within ± 0.1 division. It is probable that this represents the limit of possible accuracy of the scale when the greatest care is taken.[18] No such accuracy is attained in the average product.

Another mechanical source of error is the imperfect **balancing** of the moving system. This may be detected by holding the instrument in various positions, with no current flowing

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[15] Edgcumbe, Industrial Electrical Measuring Instruments, p. 17. Janus, Elektrotechnische Zeitschrift, 1905, p. 560.

[16] Wm. Bradshaw, Electric Journal, vol. 3, p. 395, 1906.

[17] Heinrich, Handbuch der Elektrotechnik, vol. 2, pt. 5, p. 3.

[18] Heinrich, Handbuch der Elektrotechnik, vol. 2, pt. 5, p. 7.

through it. A portable direct-current voltmeter examined in this way will show a change of zero reading of not more than a few tenths of a scale division if in good balance; millivoltmeters, wattmeters, and alternating-current instruments, all of which usually have a smaller ratio of torque to weight than the direct-current voltmeter, may show as much as one division ($\frac{1}{150}$ of a right angle). If an instrument shows considerable variation of zero reading, when examined as above, care should be taken to have it on a level support when in use as well as when it is tested. At a convenient opportunity the instrument should be put in order, preferably by the maker.

The preceding errors are inherent in the instrument; another and important class may be designated as **external errors,** or errors due to the method of use. Assuming that an instrument is well made mechanically, is properly compensated for room-temperature changes, and has no errors due to heating produced by the current, it is still possible for errors to occur. One of the most common causes is the stray field from other instruments, from conductors carrying heavy currents, or from dynamos or motors; even nonmagnetized masses of iron may affect the flux in the instrument. If possible, it is well to avoid using the instruments in exposed locations; if circumstances compel the making of tests in places subject to strong stray field, the instrument may be read, then quickly turned 180° and read again; by repeating this process several times an idea may be had of the extent to which the instrument reading is affected. The effect of stray field depends on the nature of the field and the design of the instrument. Consider the case of a stray field due to a heavy direct current; in this field is a direct-current instrument of the permanent-magnet moving-coil type. It has been shown[19] that the effect of the stray field is to change the strength of the field in which the coil moves; the distribution of this latter field is not perceptibly changed. Hence if the amount of the error be determined as above, it may be allowed for by a percentage correction for readings on any part of the scale so long as the disturbing stray field is constant in amount and direction.

With other forms of instrument the case is quite different. Take the case of an electrodynamometer voltmeter, as used for alternating current, and assume the usual case of the moving coil turning through approximately 90° for full scale deflection. A position of the instrument can be found such that the stray field produces no effect for a given reading of the instrument; in other words, for a given position of the moving coil there is no torque between it and the stray field. As the coil moves out of this position, an increasing effect of the stray field may be noted. With even a weak field, such as that due to the earth, the effect on an instrument of this type is quite appreciable, and the usual method of avoiding error in the test of such instruments consists in measuring with standard instruments the current, voltage, or power required to bring the index of the instrument under test to a given point on the scale. The direction of current is now reversed and a second measurement made, with the same reading of the instrument under test. As the effect of the earth's field is of the order of 1 or 2 per cent of the maximum scale reading, the arithmetic mean of the two values read from the standard instruments will give the value which would be found with no external field. When such an instrument is used on alternating-current circuits, stray fields such as the earth's, which do not change in direction, have no effect on the reading. Here the trouble is likely to come from heavy alternating currents of the same (or nearly the same) frequency as those in the instrument. This may be avoided to a large extent by running all leads as noninductively as possible, avoiding loops. If other sources of stray alternating flux exist, such as transformers, we may turn the instrument through 180°, noting the effect. Here also it may be possible to find a position of the coil such that the stray field exerts no torque upon the coil.

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[19] Heinrich, Handbuch der Elektrotechnik, vol. 2, part 5, p. 10.

Stray alternating fields, if not too strong, should have no effect on a permanent-magnet instrument. If the strength of field exceeds a certain value, the effect will be to partially demagnetize the magnet, making the instrument read low at the time and thereafter until repaired. An extreme case of this kind is given[20] in which a direct-current voltmeter was connected to a 600-volt circuit and placed within 18 inches of heavy alternating-current bus bars. After a severe short circuit which caused very heavy currents to flow for an instant through these bars, the voltmeter read 350 volts when the voltage applied to it was 600.

Some instruments of the electrodynamometer type are made astatic, in order to avoid error due to stray field. This is accomplished by having two moving coils so connected that a stray field produces equal and opposing torques on the two. If the stray field has the same value at the two coils, no error is produced. It is not safe, however, to assume that such instruments may be used without error in close proximity to heavy currents, as theory and experiment show that appreciable errors may result. With astatic instruments the same precautions should be taken as for the ordinary form. The results obtained will of course be more reliable.

Another source of error is that due to **electrostatic action** between the moving part of the instrument and some fixed part. Rubbing the cover glass over the needle will often cause the needle to move from its proper zero position, due to the action of an electric charge produced on the glass. The remedy for this consists in breathing on the glass, the moisture causing the charge to disappear. A similar effect has been noted when calibrating wattmeters by the method of separate sources of current and voltage. When the potential of the fixed coil is appreciably different from that of the moving coil, an electrostatic force is exerted between the two which may introduce errors into the readings. The remedy is to arrange the circuits so that the fixed coil and the moving coil may be joined together at one point. This requires care to avoid trouble due to contact between the circuits at some other point.

The **error of reading** depends partly upon the construction of the instrument, partly on the skill of the observer. Where accurate readings must be taken, it is the general custom to use an index with a flattened end, in connection with a mirror to avoid parallax. With a well-made direct-current instrument of this sort, it is possible for a skilled observer to make a reading anywhere on the scale to 0.1 mm, or about 0.1 division on the usual scale. This refers to the case of steady current or voltage; on commercial circuits, where considerable fluctuations occur, the error of reading will of course be greater.

The matter of **good electrical contact** is an important one in connection with the use of electrical instruments. One case in particular is that of the direct-current millivoltmeter used with separate shunts as an ammeter. The millivoltmeter is connected to the shunt by two leads, and in most instruments now in use this involves four contacts in the instrument circuit, two at the shunt and two at the instrument binding posts. As the resistance of the instrument is only a few ohms, a corroded or dirty terminal or binding-post surface may introduce errors which amount to several per cent. In a voltmeter of the usual 150-volt range this additional resistance would occasion no appreciable error. It would help matters if instrument makers would lay more stress on this point, and also if they would nickel plate all binding-post surfaces and cord terminals for use with millivoltmeters. One bad construction which has been practiced for years in switchboard-ammeter construction is the use of plain copper terminals, with soft-rubber tubing to prevent the cord from bending too sharply where it is soldered into the terminal. The sulphur from the rubber tubing soon blackens the copper terminals, making it necessary to clean them, even in the case of instruments not long out of the factory. **Soft-rubber tubing** should be avoided in instrument construction. Many instances have been noted in which the sulphur from soft-rubber tubing has corroded fine connecting wires until the

[20] E. P. Peck, Electrical World, vol. 51, p. 1220; 1908.

circuit was opened. This is partly due to the use of wire which is too small for mechanical reasons; the use of small stranded conductor, protected by treated cotton sleeving, is an important improvement in recent apparatus.

A bad contact at one end of an ammeter shunt, or even the use of too small a current cable at one end of the shunt, will cause that end to be heated more than the other; with many shunts now in use this will cause considerable error from thermal electromotive forces. Where it is desired to use the ordinary "station" shunts for careful work, it will help matters considerably if the shunts are placed in oil. For very large shunts, provision should be made for cooling and stirring the oil, unless current can be by-passed around the shunt for most of the time.

(i) Reliability of Electrical Instruments.

The reliability of electrical measuring instruments depends on the type, the design, and the materials and methods of construction. In general, instruments operating on the **null or balance principle** are more reliable than deflection instruments.[21] The potentiometer and the Kelvin balance operate on the null principle, while ordinary direct-reading voltmeters and ammeters are deflection instruments. Null instruments are required for work of the greatest possible accuracy, but they are expensive, slow to work with, and require very steady current and voltage. Deflection instruments are much cheaper, are quick to work with (if properly made), and do not require specially steady conditions. It is sometimes possible to combine in one instrument the null and deflection principles,[22] and thus combine, in determined proportions, the convenience of the deflection instrument and the accuracy and reliability of the null instrument.

With a given principle of operation, the reliability will still be much affected by the design. For this one must, of course, rely considerably on the skill and experience of the instrument maker; a few general principles may, however, be noted. Other things being equal, light moving systems are to be preferred to heavy ones, as the latter are more apt to occasion damage to pivots and bearings, and unless accompanied with heavy torque, will make the action slow. To design a very light moving system which shall also be sufficiently strong and give a good ratio of torque to weight is a problem requiring the highest skill. The importance of this ratio has already been referred to (p. 13).

A general principle applying to permanent magnet instruments is that the **magnetic circuit** should be as nearly closed as possible. This is stated in the following form by Heinrich:[23]

If q_m = cross section of the magnet,
l_m = length of the magnet,
q_p = cross section of air gap,
l_p = length of air gap,

then $\frac{l_m}{q_m}$ must be greater than $\frac{l_p}{q_p} \times 100$. In the usual bipolar construction, l_p is equal to twice the length of each air gap, or in general, it is the total length of air gap. A table is given by Heinrich at the reference cited, showing these four quantities for twenty different makes of direct-current switchboard instruments; drawings of the part of the magnetic circuit containing the air gap are also given. The constant above referred to, which should exceed 100, ranges from 35 (in the poorest instrument) to 500; these drawings are of interest as showing the variety of ways in which different designers will carry out the same primary idea.

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[21] H. B. Brooks, Bulletin of the Bureau of Standards, vol. 2, p. 225; 1906. See list of papers, p. 31 of this circular.

[22] H. B. Brooks, Bulletin of the Bureau of Standards, vol. 2, p. 225; 1906; vol. 4, p. 276; 1908; other matter to appear shortly. See list of papers, p. 31 of this circular.

[23] Handbuch der Elektrotechnik, vol. 2, pt. 5, p. 29.

The design should also be carefully made with reference to such details as tend to rigidity, strength, and permanence of adjustments. Given a good design, it is still essential that first-class material be used; for example, the use of inferior or unsuitable steel for magnets would result in an instrument whose indications would change greatly with time, even with good design. Given a good fundamental principle, a good design, and good material, the result still depends on good workmanship; for example, with the best magnet steel improperly treated the results would be inferior. These considerations show upon what complex conditions the reliability of electrical instruments depends, and to what a large extent the experience, facilities, and shop system of the maker affect the result. It is also evident that even the best makers may occasionally turn out an instrument whose reliability is markedly inferior to the general average for the type, and that for all careful work there should be provided some means for checking the working instruments by others not subject to the same sources of error.

(*j*) Apparatus for Checking Instruments.

Primary standard instruments, properly so called, are not suitable for general use, but should be maintained in a few well-equipped laboratories. The instruments used to check working instruments may properly be called secondary standards. They should be checked by a national standardizing bureau, or by such college or other laboratories as are prepared to do this work. The secondary standards to be provided will depend considerably upon the number and kind of the working instruments to be tested, and may be considered in connection with the method of using them.

Fundamental electrical standards, with few exceptions, are essentially for direct current. It is therefore necessary first of all to provide a good **potentiometer, standard cells,** and **standard resistances.** Using these, accurate measurements may be made of the three fundamental quantities—electromotive force, current, and resistance. Necessary adjuncts to the potentiometer are the storage cell for furnishing the current, the regulating rheostat, and the galvanometer.[24]

The Clark cell was formerly much used as a secondary standard, but it has an objectionably large temperature coefficient, and also a time lag of electromotive force behind the temperature. The most convenient standard cell for general laboratory use is unquestionably the Weston unsaturated cell, as supplied by the Weston Electrical Instrument Company. In this cell the temperature coefficient is negligible for all commercial and for very many laboratory purposes. The constancy of these cells is very satisfactory, but as a check against possible changes due to improper handling, more than one cell should always be provided. It is convenient to use three cells. If two of these agree while the third fails to check with them, the two may be used while the third is sent to a standardizing bureau for test.

The fundamental range of the usual standard potentiometers being about 1.5 volts, it is necessary to provide **volt boxes** for ranges higher than this. These are simply resistance boxes in which a certain total resistance is connected to the line whose voltage is to be measured, while the potentiometer is connected across a definite fraction of the resistance, usually one-tenth, one-hundredth, etc. Ordinary resistance boxes of known value may be used in this way for low voltages, but for the usual commercial lighting and power voltages this practice is not to be recommended. Special volt boxes should be used, designed for the purpose, with a suffi-

[24] The mistake is sometimes made of associating a potentiometer with any galvanometer at random. The best results as regards convenience, speed of working, and sensibility are obtained only when the galvanometer has a sensibility and critical resistance that suit it to the windings of the potentiometer. Thus a high-resistance galvanometer of high external critical resistance will not give the best results when used with a low-resistance potentiometer. See W. P. White, Physical Review, vol. 25, p. 334; 1907.

cient number of coils to cut down the dielectric stress per coil to a safe value, and with proper separation and insulation of the terminals.

For the measurement of current there will also be required a set of manganin **resistance standards,** or shunts. These are usually made for oil immersion, and give about one volt drop at full load; this makes the full load reading come well up on the potentiometer scale. For very heavy currents it is advisable to have a lower full-load drop, to keep down the size of the shunt; the precision required for such heavy currents is usually less than for more moderate ones, so the reduced sensibility of reading is no objection. Some potentiometers are provided with a shunting arrangement so that the range may be changed from 0 to 1.5 volts to 0 to 0.15 volt; with a sufficiently sensitive galvanometer this enables a good sensibility to be had with a shunt giving a drop of 0.1 volt at full load. The fact is often overlooked, however, that such a method of operation sacrifices the accuracy of the result to a certain extent. Even with manganin shunts there are slight thermal electromotive forces, and such electromotive forces often exist in the potentiometer contacts, in the junctions of connecting leads, and in the galvanometer, especially when the latter has steel suspensions. The resultant of all these electromotive forces introduces an error which is proportionately greater the lower the drop on the shunt. As the current in such measurements is supplied by storage cells, the apparatus under test, circuit connections, regulating rheostat, and standard shunt must have a total drop of at least 2 volts, one-half of this being usually sufficient for all the items except the standard shunt, which may then have a drop of 1 volt. It is true that air-cooled shunts for large currents, to give 1 volt drop, become large and expensive, but where the apparatus is not to be removed from the laboratory, there is little disadvantage in the use of oil cooling; the temperature of the resistance material is kept much lower and may be much more accurately determined.

Resistance standards for such work are made by a number of makers in this country and abroad. Their general form and construction have become more or less standard, following the designs originally worked out at the Reichsanstalt. Those by the best makers give results which leave little to be desired for commercial purposes, although as precision standards improvements are still desirable.

To supply current for such work as the testing of ammeters, it is convenient to have, say, four **storage cells** with a switchboard having eight single-pole double-throw switches. By means of these the cells may be connected all in parallel for discharge at 2 volts; in parallel-series for 4 volts, or all in series for discharge at 8 volts, or for charging. A voltmeter should be provided which will read (by means of a voltmeter switch) the voltage of each cell separately, or (on a higher scale) the voltage of the discharge circuit. This assists in determining the condition of individual cells. There should be an ammeter in the discharge circuit, and preferably one in series with each cell; the scale of these latter ammeters should have the zero so located that the maximum discharge current may be read by the movement of the index toward the right, while the maximum charging current is read by movement to the left.

Such a set of cells is also useful for supplying direct current to the series coils of wattmeters and watthour meters, and many other purposes. For the voltage circuits of such instruments, and for direct-current voltmeters, it is desirable to have sets of smaller cells of, say, 8 to 20 ampere-hours capacity, the number depending on the maximum voltage to be supplied, and the ampere-hour capacity depending on how large a current will be drawn at any time, and what degree of steadiness of the voltage is required.

The foregoing discussion outlines the most essential parts of an equipment for making precision tests of direct-current instruments. Where the most refined precision is required, and accurate measurements must be made of very small electromotive forces, such as those

due to thermocouples, the potentiometer should be of the usual four or five dial form, or equivalent, and should operate as a null instrument, no current being drawn from the source, except when using a volt box. With this type of potentiometer the equipment of storage cells just referred to can not be dispensed with, as the fluctuations of commercial circuits make it impossible to use current and voltage from them. Where a class of work is to be done in which the measurement of voltages of 1 volt and higher to an accuracy of one-twenty-fifth of 1 per cent (voltages below 1 volt to a lower accuracy) is sufficient, and the same degree of accuracy for currents above 0.03 ampere, it is possible to use a **deflection potentiometer,** in which both null and deflection principles are used. These potentiometers measure the bulk of the unknown current or voltage by the null principle, thus securing accuracy and reliability; the small margin of the result is read by the deflection of a pivoted moving-coil galvanometer resembling an ordinary direct-current voltmeter, thus securing quickness in reading. These potentiometers may be used on commercial circuits, as the changes in current or voltage are quickly followed by the index of the galvanometer, which is designed to be just aperiodic, taking up a new position without oscillation. If the circuit is fairly steady, one observer can go quickly from the instrument under test to the potentiometer, and get a good check of the former by taking several readings. If the circuit is quite unsteady, as when motors are operated from it, two observers may read the two instruments simultaneously at the momentary lulls which occur. Using storage batteries, the deflection potentiometer enables the accurate testing of direct-current instruments in very much less time than with any other method. These potentiometers were designed at this Bureau[25] for its own use in such work, and also with reference to the needs of instrument makers, central station and other commercial laboratories, where accuracy and speed must be combined.

For the testing of alternating-current instruments it is necessary to provide, in addition to the foregoing, an equipment of suitable **transfer instruments**—that is, instruments which can be calibrated on direct current and used without error (or with small and determined error) on alternating current. The most suitable instruments for this purpose are of the electrodynamometer type, and for convenience of working they should usually be of the pivoted form, as suspension instruments, while indispensable for accurate laboratory purposes, are too troublesome and slow for commercial work. A portable **electrodynamometer voltmeter** of good construction, with suitable multipliers, enables alternating voltages of moderate value to be readily measured. The inductance of this instrument should be determined, in order that frequency errors may be known and allowed for if necessary; for a good instrument of this type on the usual commercial frequencies this error will be quite small. For higher voltages, say over 750, such a voltmeter may be used in connection with a well-made potential transformer whose ratio of transformation has been carefully determined. It should be borne in mind that this ratio is varied by changing the secondary load; it is advisable to have curves for the transformer, showing its ratio from no load to full load, for the frequencies to be used.

For the measurement of alternating current power, well-made **electrodynamometer wattmeters** should be used. In such instruments the inductance of the potential circuit will introduce no error of any practical consequence except at very low power factors.[26] The effect of **eddy currents** in badly designed wattmeters is often more serious than that of inductance in the potential circuit. When the power of heavy currents is to be measured, or when safety to the operator requires that the wattmeter shall not be directly connected to the line,

[25] H. B. Brooks, Bulletin of the Bureau of Standards, vol. 2, p. 225, 1906; vol. 4, p. 275, 1908; other matter soon to appear. See list of papers, p. 31 of this circular.

[26] The accurate measurement of alternating current power at very low power factors requires special methods and apparatus. See paper by E. B. Rosa, Bulletin of the Bureau of Standards, vol. 1, p. 383, 1905. See list of papers, p. 31 of this circular.

current transformers or potential transformers, or both, may be required. The secondary current is then not exactly in opposition to the primary, and the secondary voltage is not exactly in opposition to the line voltage. The effect of these small discrepancies in phase (referred to as the "phase angles" of the transformers) is small for noninductive load, but may become relatively considerable at very low power factors.[27]

For the measurement of alternating currents of moderate value, say not over 200 amperes, **electrodynamometer ammeters** are made which may be calibrated on direct current and used on alternating current of commercial frequencies with small error. For heavier currents the most convenient method is to use an ammeter of this type for 5 amperes in connection with a **precision current transformer;** that is, a transformer of good design for the purpose, well made and of good material. Such a transformer and ammeter may be tested by a properly equipped standardizing bureau at the frequencies at which they are to be used, the two being separately checked. The transformer may then be considered as constant, and the user can determine and allow for any change in the ammeter by checking it on direct current with the potentiometer. Such transformers are sometimes made with two or three ranges; this adds to their convenience by enabling a good reading of the ammeter to be had for a large range of current.

The phase angle between primary and secondary currents introduces no error when a current transformer is used with an ammeter; but in this case, as in that of the wattmeter, it should be remembered that the ratio of transformation varies with the primary current for a given transformer and set of instruments connected to its secondary; for the same primary current the ratio will be changed if the resistance and reactance of the secondary circuit are changed, as by changing the number, type, or range of instruments operated.

In addition to the foregoing principal items, accessory apparatus will be required. The amount and kind of this apparatus will depend on the nature and extent of the work to be done. A **Wheatstone bridge** should be provided, and should preferably be set up with battery and galvanometer, ready for instant use. Measurements should be made of the resistance of voltmeters, potential circuits of wattmeters, multipliers, etc., at the time these are received from the maker. These values should be recorded, and when the instruments are brought in later for check the measurement of resistance should be repeated. Often a defective contact in a key or a loose wire connection will be found by the bridge measurement before the trouble becomes great enough to be detected in service.

There should be provided a supply of **resistance boxes;** few of these need be of high precision, as instrument makers supply resistance boxes adjusted to a moderate degree of accuracy for a moderate price. It is usually better to have a large number of such moderate-priced boxes than a few high-priced ones, which are "too good to use" for many purposes. Where a moderate-priced box is used in a piece of work where its resistance needs to be accurately known, it may be checked by bridge measurements; this assumes that the coils and contacts are well made, so that no variable resistances occur. In addition there will be required a number of ordinary **rheostats** for the control of current and voltage. Field rheostats of standard make may be used in many cases; where a finer regulation is wanted, a slide resistance may be used. These are made by winding resistance wire on an insulated tube, or on a bar of slate or other insulating material. A sliding contact is arranged to run along the wound surface. These are available in a large variety of sizes and resistances at moderate prices.

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[27] See paper by L. T. Robinson, Transactions American Institute of Electrical Engineers, vol. 28, 1909. This paper gives numerical examples, and tables to facilitate computation.

Carbon rheostats are useful where the current must be controlled with very great nicety; these lower in resistance as they heat up, thus tending to balance the increase of resistance of the copper in the circuit. They can not be set to definite values of resistance, and will change in resistance if not constantly controlled.

For the measurement of **frequency,** instruments of the resonance or vibrating reed type are very useful. They are free from errors due to variation of voltage and wave form, which affect the reading of most other types of frequency meter. These instruments are made in a convenient portable form, and may be placed in any position near the work; it may thus be seen at a glance whether the frequency is correct.

It is convenient in many cases to have **indicating instruments** in the test circuits, partly as a means of roughly checking results and also to avoid overloading apparatus and circuits. Good electromagnetic (soft-iron) instruments are very useful in this connection, as they will give results correct to within a few per cent on direct current and to much better accuracy on alternating current. They may now be had at such reasonable prices that a good supply may be provided. When better accuracy on direct current is required, the permanent-magnet moving-coil instrument should be used; these are available in moderate-priced types from most makers.

Where it is desired to measure **inductance** to moderate accuracy, the use of a variable inductance standard in connection with the Wheatstone bridge gives good results. As ordinarily made, such a variable inductance is a rather large and expensive piece of apparatus; some firms meet the need for a smaller and lower-priced standard in a construction which is ample for the above purpose. The measurement of capacity may also be made with the Wheatstone bridge, using a standard condenser. The precision testing of inductances and capacities is treated in another circular.

To supply heavy currents for alternating-current ammeters and the current coils of wattmeters and watthour meters, **transformers** should be provided, with secondary voltage of 2 and 4 volts, or 4 and 8 volts, depending on the length and size of leads, the drop in each instrument, and the number of instruments to be in circuit at one time. The precision ammeters of the electrodynamometer type require several volts (the amount varies with the range) to pass full-load current through them; it is advisable to have the secondary voltage high enough to give a little margin over anticipated requirements.

In addition to the galvanometers used with the Wheatstone bridge and potentiometers, it is often convenient to have **portable galvanometers** which can be used anywhere without any special leveling or other adjustments. The ordinary direct-current voltmeter may be wound with a considerably larger number of turns of wire than usual and provided with weaker springs; this gives a very convenient instrument for some work. With the usual 150-division scale, covering about a right angle, a good instrument of this kind will give one scale division for about 5 microamperes, or full scale for less than a milliampere. The resistance of the coil in this case would be 500 or 600 ohms. This refers to an instrument intended for high current sensibility; for high volt sensibility the winding would be of coarser wire, other things remaining the same. If the length of scale may be reduced, the pole pieces may be made to cover a smaller arc; this increases the strength of the field in which the coil moves, and increases the sensibility. If such instruments are to be used permanently in a definite arrangement of apparatus, it is desirable to have the galvanometer and the apparatus so designed that the motion of the coil shall be dead beat. If a portable instrument of still higher sensibility is desired, this may be had by abandoning the pivot construction for suspensions. Such instruments, with reading telescope, are now on the market.

Other details of an outfit for instrument testing, such as keys, switches, cables, etc., will depend upon the work to be done, and their selection offers no special difficulties. The Bureau will be glad to advise and assist in selecting an equipment of apparatus, and invites correspondence and personal visits from those interested.

In the testing of electrical measuring instruments, as done at the Bureau of Standards, measurements of direct electromotive force are made by means of potentiometers and Weston cells, the values of the latter being known in terms of the standards of the Bureau. Direct currents are measured by the above, with the addition of standard resistances. Alternating electromotive force, current, and power are measured by means of specially constructed electrodynamometers which admit of accurate calibration by means of direct current. Thus all current, voltage, and power measurements, direct and alternating, are referred to standard resistances and standard cells.

The alternating-current instruments employed are as free as possible from errors due to inductance, eddy currents, etc., and where necessary, corrections are applied for the effects due to small residual inductances. Special generating apparatus is employed, enabling the voltage, frequency, power factor, and wave form of electric currents to be controlled and varied as desired, and every effort is made to secure accurate measurements.

2. REGULATIONS.

(*a*) Application for Test.

The request for test of any instrument should state fully the conditions under which the test is to be made, including the temperature, number of points to be tested, etc. The number of points at which instruments are regularly tested is given for each class of instrument in the schedule of fees for that class. If additional points are desired, or if particular points are preferred for the regular test, it should be so stated. In sending multiple-range instruments, it should be stated on what range or ranges the test is to be made, and the number and location of points on each range. In the case of simple instruments sent in for test, with no specifications as to conditions, the Bureau may decide what the nature of the test should be, without correspondence.

(*b*) Identification Marks.

Instruments and the packages in which they are shipped should both be plainly marked to facilitate identification, preferably with the name of the manufacturer or shipper, and a special reference number given to the article. This number may usually be the maker's serial number.

(*c*) Shipping Directions.

Instruments should be securely packed in cases or packages which may be used in returning them to the owner. Except in the case of heavy apparatus not liable to damage in transit (for example, transformers), it is recommended that shipment be made by express. Transportation charges are payable by the party desiring the test, and should be prepaid. Unless otherwise arranged, articles will be returned by express "collect."

Great care should be taken in packing instruments for shipment. Boxes should be sound and strong; the tops should be preferably in one piece or of several pieces dovetailed together and should be screwed down, as the jar due to nailing and the subsequent opening is liable to damage pivots and other delicate parts of the apparatus. Clean, fresh excelsior is a very suitable packing material. The boxes used should be large enough to allow for 3 inches

or more of excelsior all around each instrument. When electrical measuring instruments of good construction are carefully packed as above described and sent by express, it is the experience of this Bureau that change of calibration or other damage is very infrequent. It is a good precaution to wrap each instrument in oilcloth or other moisture-proof fabric. If this is not done, it should be carefully wrapped in strong paper to prevent dust and particles of excelsior from getting into the instrument.

(*d*) Address.

Articles should be addressed simply, "Bureau of Standards, Washington, D. C." Delays incident to other forms of address will thus be avoided.

Articles delivered in person or by messenger should be left at the shipping office of the Bureau and should be accompanied by a *written request* for the test.

(*e*) Remittances.

Fees should be sent with the request for test in accordance with the schedules of fees following, and may be remitted by money order or check drawn to the order of the "Bureau of Standards."

Delays in forwarding fees will involve corresponding delay in the completion of tests, as the articles are not returned until all fees due thereon have been received.

3. GENERAL INSTRUCTIONS.

When electrical instruments are submitted for test, it is very desirable that the request be accompanied by a statement giving as far as possible the conditions under which the apparatus is used, and the conditions under which the test is desired. For example, in submitting an indicating wattmeter of the electrodynamometer type for test, it should be stated whether test is to be made on direct current, alternating current, or a separate test on each; the number and location of points on the scale at which test is desired, with the voltage to be used; if test is to be made on alternating current, the frequency and power factor should also be given. (In the absence of instructions to the contrary, a sine wave form is always used.) It is only when such full information is given that the most accurate results can be had for any given case; in many instances it is necessary to delay the test until the required information can be obtained by correspondence.

All instruments must be in good operative condition, in order to be admitted for test. *No repair work will be done;* such work should usually be done by the maker of the instrument. If there are any unusual circumstances in connection with the instrument, it will save time if the facts are stated. For example, an instrument having a large zero error may have been in use, and test may be desired with the instrument in this condition. To avoid delay and correspondence, this fact should be stated; otherwise, the assumption may be made that the instrument has suffered injury in transit, and the test will be delayed until the matter is settled by correspondence.

Electrical instruments will be tested at ordinary room temperature, averaging about 25° C (77° F), being lower than this in winter and higher in summer. If test at a specified temperature is desired, this may be had, if practicable, for an extra fee.

Whenever possible, the request should be accompanied by the fee as shown in the appended schedules.

When it is necessary that instruments sent in for test shall be returned within a specified time, arrangements for the test should be made in advance of shipment. The Bureau can not undertake to make tests upon receipt of apparatus, except in special cases. It is desirable in all cases to arrange for the test before sending the apparatus.

In addition to the testing of electrical measuring instruments, as described in this circular, the Bureau tests other electrical apparatus, as follows: Resistance apparatus of precision, including resistance standards of 0.0001 ohm to 100,000 ohms; bridges, potentiometers, and precision rheostats; standard cells. Determinations are also made of the conductivity, temperature coefficient, and thermoelectric properties of metals. Full information in regard to this work will be given in a later circular. The accurate determination of the capacity, power factor, and other constants of condensers, and the inductance of coils will be covered by another circular, and photometric work in a third. Magnetic testing is described in Circular No. 17. These circulars will be sent to interested parties on request.

4. SCHEDULE OF FEES.

The fees given in the following schedule apply to regular commercial instruments as used in practical work; these instruments are understood to be of the deflection type, requiring no special manipulation to get a reading. It is not possible to give a general statement of the accuracy of the test, as so much depends on the type and construction of the instrument tested. Where the instruments submitted for test are of the balance type (such as Kelvin balances and other instruments on this principle), and hence require more time to secure readings, or where deflection instruments or other commercial apparatus are to be tested with a greater degree of accuracy than would ordinarily be required, *the fees charged will be twice those stated, or more,* depending on the amount of labor involved. This applies also to instruments having any unusual characteristics which increase the difficulty or labor of making the required tests.

Instruments sent in for test sometimes develop faults which are not apparent at the beginning of the test. In such a case, when an appreciable part of the work has been done, a charge will be made which will bear the same proportion to the fee for a complete test that the amount of work done bears to the work of making the complete test.

The fees given in Bureau Circular No. 6 of February 20, 1906, are superseded by those given in the following schedules.

Schedule 81.

I.—*Direct-current ammeters.*

Test at five points:

(*a*) Not exceeding 50 amperes	$1.50
(*b*) Exceeding 50 and not exceeding 250 amperes	2.00
(*c*) Exceeding 250 and not exceeding 500 amperes	3.00
(*d*) Exceeding 500 and not exceeding 1,000 amperes	5.00
(*e*) Exceeding 1,000 and not exceeding 5,000 amperes	8.00
(*f*) Exceeding 5,000 and not exceeding 10,000 amperes	12.00

(*g*) Each additional point above five will be charged one-tenth of the base fee.

(*h*) For the determination of the temperature coefficient, in addition to the corrections at five points, the total fee will be double that stated above.

i) Each additional instrument after the first, to be tested at the same time and through the same range,[28] will be charged one-half of the base fee as given above.[29]

(*j*) For the determination of the effect of continued current on the readings, the additional fee will be one-half the base fee as given above.

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[28] If additional instruments are not of identically the same range, but still come within the same limits as the first instrument, each such additional instrument will be charged one-half of the fee for the first instrument.

[29] This one-half rate applies only to the five-point test; additional points for the additional instrument will each be charged one-tenth of the base fee as given in the schedules.

Combinations consisting of a millivoltmeter and a shunt will be tested together at the above rates. If a separate test of each is desired, with the corrections for each, the fees will be charged according to the above schedule for the shunt, and 81—II for the millivoltmeter.

II.—*Direct-current voltmeters and millivoltmeters.*

Test at five points:

(*m*) Not exceeding 300 volts, at one temperature $1.50
(*n*) Exceeding 300 volts and not exceeding 750 volts 2.50
(*o*) Exceeding 750 volts and not exceeding 1,500 volts 5.00
(*p*) Each additional point above five will be charged one-tenth of the base fee.
(*q*) For the determination of the temperature coefficient, in addition to the corrections at five points, the total fee will be double that stated above.
(*r*) Each additional instrument after the first, to be tested at the same time and through the same range,[30] will be charged one-half of the base fee as given above.[31]

When instruments falling under Schedule 81 are submitted for test, without specific instructions, single-range instruments will be tested at five points. Multiple-range instruments will be tested at five points on each range. The fee for the highest range will be taken from the above schedule; the remaining points will be charged for by 81 (*p*), using as base fee that for the highest range.

Schedule 82.

I.—*Alternating-current ammeters.*

Test at five points:

(*a*) Not exceeding 50 amperes, tested at one frequency and one temperature, using currents of approximately sine wave form $2.00
(*b*) Exceeding 50 amperes and not exceeding 250 amperes, tested as above 3.00
(*c*) Exceeding 250 amperes and not exceeding 500 amperes, tested as above 5.00
(*d*) Exceeding 500 amperes and not exceeding 1,000 amperes, tested as above 8.00
(*e*) Each additional point above five will be charged one-tenth of the base fee.
(*f*) For each additional frequency[32] at which a test is made at five points, the additional fee will be one-half of the above rates.
(*g*) For each additional wave form[32] at which a test is made at five points, the additional fee will be equal to fee named above for the original test.
(*h*) For the determination of the temperature coefficient an extra fee will be charged equal to that given above. This involves a test at three temperatures, about 10°, 25°, and 40° C, unless otherwise specified. Where instruments are to be used in water-power plants, or other places where low temperatures are likely to prevail, or in engine rooms at relatively high temperatures, they may be tested at temperatures outside this range anywhere between 0° and 50° C.
(*i*) Each additional instrument after the first, to be tested at the same time and through the same range,[30] will be charged one-half of the base fee as given above.[31]
(*j*) When the same instrument is tested both with direct and with alternating current, the fee will be 50 per cent more than for a test with alternating current only.

When alternating ammeters are used with current transformers, they may be tested together as one apparatus at the above rates. If a separate test is required for each, they will be counted

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[30] If additional instruments are not of identically the same range, but still come within the same limits as the first instrument, each such additional instrument will be charged one-half of the fee for the first instrument.

[31] This one-half rate applies only to the five-point test; additional points for the additional instrument will each be charged one-tenth of the base fee as given in the schedules.

[32] These fees are based on a moderate range of frequency and wave form, and a moderate degree of approximation to the customer's specifications for the wave form. Extreme frequencies, unusual wave forms, or the necessity for closely following specifications for the wave form, will be subject to a special extra fee. Such tests should always be arranged for in advance of shipment of the apparatus.

as two pieces of apparatus, and the fee will be charged accordingly. The separate test is to be preferred, as the transformer will in all probability have a very constant ratio over a long period of time, while the ammeter usually has springs or other elements subject to change with time. When transformer and ammeter are tested separately, it is thereafter sufficient to test the ammeter alone, at suitable intervals.

II.—*Alternating-current voltmeters.*

Test at five points:

(*m*) Not exceeding 300 volts, tested at one frequency and one temperature, using electromotive forces of approximately sine wave form	$2.00
(*n*) Exceeding 300 volts and not exceeding 750, tested as above	3.00
(*o*) Exceeding 750 volts and not exceeding 1,500, tested as above	5.00
(*p*) Exceeding 1,500 volts and not exceeding 3,000, tested as above	7.00
(*q*) Exceeding 3,000 volts and not exceeding 7,000, tested as above	10.00
(*r*) Exceeding 7,000 volts and not exceeding 12,000, tested as above	15.00
(*s*) Exceeding 12,000 volts and not exceeding 17,000, tested as above	20.00

(*t*) Each additional point above five will be charged one-tenth of the base fee.

(*u*) For each additional frequency[33] at which a test is made at five points, the additional fee will be one-half the base fee as given above.

(*v*) For each additional wave form[33] the additional fee will be equal to the base fee as given above.

(*w*) For the determination of the temperature coefficient an extra fee will be charged equal to that given above. (See 82 (*h*).)

(*x*) Determination of the inductance and resistance of an alternating-current voltmeter	1.00

(*y*) Each additional instrument after the first, to be tested at the same time and through the same range,[34] will be charged one-half the base fee as given above.[35]

When alternating voltmeters are used with potential transformers, they may be tested together as one apparatus at the above rates. If a separate test is required for each, they will be counted as two pieces of apparatus and the fee will be charged accordingly. The separate test is to be preferred, as the transformer will in all probability have a very constant ratio over a long period of time, while the voltmeter usually has springs or other elements subject to change with time. When transformer and voltmeter are tested separately, it is thereafter sufficient to test the voltmeter alone, at suitable intervals.

When instruments falling under Schedule 82 are submitted for test, without specific instructions, sinusoidal alternating current or voltage will be used, of 60 cycles frequency, unless some other frequency is clearly marked on the instrument. Multiple-range instruments will be tested at five points on each range. The fee for the highest range will be taken from the above schedule; the remaining points will be charged for by 82 (*e*), using as base fee that for the highest range.

Schedule 83.—Wattmeters.

I.—*Tested with direct current.*

Test at five points:

(*a*) Not exceeding 5 kilowatts, at one temperature	$2.00
(*b*) Exceeding 5 kilowatts, not exceeding 25 kilowatts, at one temperature	3.00

[33] These fees are based on a moderate range of frequency and wave form, and a moderate degree of approximation to the customer's specifications for the wave form. Extreme frequencies, unusual wave forms, or the necessity for closely following specifications for the latter will be subject to a special extra fee. Such tests should always be arranged for in advance of shipment of the apparatus.

[34] If additional instruments are not of identically the same range, but still come within the same limits as the first instrument, each such additional instrument will be charged one-half the fee for the first instrument.

[35] This one-half rate applies only to the five-point test; additional points above five, at the additional frequency or wave form, will each be charged for at one-tenth of the base fee.

(c) Exceeding 25 kilowatts, not exceeding 100 kilowatts, at one temperature $5.00
(d) Each additional point above five will be charged one-tenth of the base fee.
(e) For the determination of the temperature coefficient, an additional fee equal to the above will be charged. (See 82 (h).)
(f) For the determination of the inductance and resistance of the potential circuit of a wattmeter which is being tested, the additional fee is 1.00

II.—*Tested with alternating current.*

Test at five points, at one frequency and one temperature, with unity power factor and approximately sine wave form:

(m) Not exceeding 5 kilowatts $3.00
(n) Exceeding 5 kilowatts, not exceeding 25 kilowatts, tested as above 4.00
(o) Exceeding 25 kilowatts, not exceeding 100 kilowatts, tested as above 6.00
(p) Each additional point above five will be charged one-tenth of the base fee.
(q) For each additional frequency[36] at which a test is made at five points, the additional fee will be one-half of the base fee as given above.
(r) For each additional wave form[36] the additional fee will be equal to the base fee.
(s) For the determination of the temperature coefficient an additional fee equal to the base fee will be charged. (See 82 (h).)
(t) For a test at five points at each additional power factor, half of the base fee as given above.
(u) When the same instrument is tested both by direct and alternating currents, the fee will be 50 per cent more than for test with alternating current only.
(v) The above fees apply to single-phase wattmeters; the base fees for polyphase wattmeters will be twice those for single-phase.
(w) Each additional instrument after the first, to be tested at the same time and through the same range[37], will be charged one-half the base fee as given above.[38]

When instruments falling under Schedule 83 are submitted for test, without specific instructions, wattmeters operating equally well on direct and on alternating current will be tested with direct current at five points. Wattmeters nominally for 150 volts will be tested at 110 volts; suitable values of current will be used. Wattmeters operating only on alternating current (induction type) will not be tested except on receipt of detailed instructions as to voltage, frequency, power factor, and number of points at which test is to be made.

Schedule 84.—Watthour Meters.

I.—*Direct-current meters.*

Test at five loads, viz, 10 per cent, 25 per cent, 50 per cent, full load, and 50 per cent overload, unless otherwise ordered:

(a) Not exceeding 5 kilowatts $3.00
(b) Exceeding 5 kilowatts, not exceeding 25 kilowatts 4.00
(c) Exceeding 25 kilowatts, not exceeding 100 kilowatts 6.00
(d) For the determination of the temperature coefficient, an additional fee equal to twice the base fee, as given above, will be charged. This determination will be made at one-tenth and at full load, unless otherwise ordered.
(e) Each additional meter after the first, to be tested at the same time and through the same range,[37] will be charged one-half of the above rate.[38]
(f) Each additional load above five will be charged one-tenth of the base fee.

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[36] These fees are based on a moderate range of frequency and wave form, and a moderate degree of approximation to the customer's specifications for the wave form. Extreme frequencies, unusual wave forms, or the necessity for closely following specifications for the latter, will be subject to a special extra fee. Such tests should always be arranged for in advance of shipment of the apparatus.

[37] If additional instruments are not of identically the same range, but still come within the same limits as the first instrument, each such additional instrument will be charged one-half of the fee for the first instrument.

[38] This one-half rate applies only to the five-point test; additional points for the additional instrument will each be charged one-tenth of the base fee as given in the schedules.

II.—*Alternating-current watthour meters, single phase.*

Test at one frequency, unity power factor, rated voltage, and approximately sine wave form on five different loads, viz, 10 per cent, 25 per cent, 50 per cent, full load, and 50 per cent overload, unless otherwise ordered:

(*l*) Not exceeding 5 kilowatts $3.00
(*m*) Exceeding 5 kilowatts, not exceeding 25 kilowatts 4.00
(*n*) Exceeding 25 kilowatts, not exceeding 100 kilowatts 6.00
(*o*) For each additional frequency[39] at which a test is made at five loads, the additional fee will be one-half of the base fee.
(*p*) For each additional power factor at which a test is made at five loads, the additional fee will be one-half the base fee.
(*q*) For each additional voltage at which a test is made at five loads, the additional fee will be one-half the base fee.
(*r*) For each additional wave form[39] at which a test is made at five loads, the additional fee will be equal to the base fee.
(*s*) For the determination of the temperature coefficient, an additional fee equal to twice the base fee will be charged. This determination will be made at one-tenth and at full load, unity power factor, unless otherwise ordered.
(*t*) Each additional meter after the first, to be tested at the same time and with the same loads, will be charged one-half the base fee.[40]
(*u*) Each additional load above five will be charged one-tenth of the base fee.

III.—*Polyphase watthour meters.*

(*v*) Polyphase watthour meters will be charged twice the foregoing rates for single-phase meters.

Instruments falling under Schedule 84 must in all cases be accompanied by full instructions as to the nature of the test desired.

SCHEDULE 85.

Phase meters, power-factor meters, and frequency meters.

Test at five points; current ranges not over 100 amperes; voltage ranges not over 250 volts.

(*a*) Phase meters and power-factor meters, at one frequency[39] and one load, using approximately sine wave form . $5.00
(*b*) Each additional test at five points for other frequencies or other loads 2.50
(*c*) Frequency meters, at one voltage, using approximately sine wave form 3.00
(*d*) Each additional test at other voltages 1.50
(*e*) Each additional point above five will be charged one-tenth of the base fee.
(*f*) For each additional wave form[39] the additional fee will be equal to the base fee.
(*g*) Each additional instrument after the first, to be tested at the same time and at the same points, will be charged one-half the base fee as given above.[40]

Instruments falling under Schedule 85 must in all cases be accompanied by full instructions as to the nature of the test desired.

SCHEDULE 86.—INSTRUMENT TRANSFORMERS.

I.—*Current transformers.*

Test for ratio of transformation (quotient of primary or line current divided by secondary or meter current) with a given load of instruments (or specified resistance and reactance) connected to the secondary, at five values of primary current, viz, 10 per cent, 20 per cent, 40 per cent, 60 per cent, and full load, unless otherwise ordered; secondary full-load current not exceeding 10 amperes:

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[39] These fees are based on a moderate range of frequency and wave form, and a moderate degree of approximation to the specifications for the wave form. Unusual frequencies or wave forms, or the necessity for closely following specifications for the latter, will be subject to a special extra fee. Such tests should always be arranged for in advance of shipment of the apparatus.

[40] This one-half rate applies only to the five-point test; additional points for the additional instrument will each be charged one-tenth of the base fee as given in the schedules.

(*a*) Primary current not exceeding 50 amperes, tested at one frequency, using currents of approximately sine wave form $3.00
(*b*) Exceeding 50 amperes and not exceeding 250 amperes, tested as above 4.00
(*c*) Exceeding 250 amperes and not exceeding 500 amperes, tested as above 5.00
(*d*) Exceeding 500 amperes and not exceeding 1,000 amperes, tested as above 8.00
(*e*) Each additional current above five will be charged one-tenth of the base fee.
(*f*) For each additional frequency[41] at which a test is made at five currents, the additional fee will be one-half of the base fee.
(*g*) For each additional secondary load (of instruments, or specified resistance and reactance) at which a test at one frequency is to be made with five values of primary current, the additional fee will be one-half the base fee.
(*h*) Each additional transformer after the first, to be tested at the same time and through the same range, will be charged one-half of the base fee as given above.[42]
(*i*) For the determination of the phase angle between primary and secondary currents, in addition to the ratio, for five values of primary current as above, the additional fee will be one-half the base fee as given above.

II.—*Potential transformers.*

Test for ratio of transformation (quotient of primary applied voltage divided by secondary terminal voltage) with a given primary voltage, and five values of secondary load, namely, no load, 50 per cent, and full load, unity power factor; 50 per cent and full volt-amperes,[43] approximately 20 per cent power factor, unless otherwise ordered:

(*a*) Primary voltage not exceeding 300 volts, tested at one frequency, using electromotive forces of approximately sine wave form $3.00
(*b*) Exceeding 300 volts and not exceeding 750, tested as above 4.00
(*c*) Exceeding 750 volts and not exceeding 1,500, tested as above 5.00
(*d*) Exceeding 1,500 volts and not exceeding 3,000, tested as above 7.00
(*e*) Exceeding 3,000 volts and not exceeding 7,000, tested as above 10.00
(*f*) Exceeding 7,000 volts and not exceeding 12,000, tested as above 15.00
(*g*) Exceeding 12,000 volts and not exceeding 17,000, tested as above 20.00
(*h*) Each additional load above five will be charged one-tenth of the base fee.
(*i*) For each additional frequency[41] at which a test is made at five loads, the additional fee will be one-half of the base fee.
(*j*) For each additional primary voltage at which a test at one frequency is to be made with five values of secondary load, the additional fee will be one-half the base fee.
(*k*) Each additional transformer after the first, to be tested at the same time and through the same range, will be charged one-half of the above fees.[44]
(*l*) For the determination of the phase angle between primary and secondary voltages, in addition to the ratio, for five values of secondary load as above, the additional fee will be one-half the base fee as given above.

5. SPECIAL TESTS AND MEASUREMENTS.

In addition to the usual tests given in the foregoing schedules, the Bureau is prepared to make tests of dielectric strength (using alternating electromotive forces) up to 20,000 volts, on samples of insulating material, insulated wire, insulating joints, etc. It is expected that this range will be considerably extended in the near future. Determinations may be made of the wave forms used in the alternating-current tests scheduled, or of the wave forms of small machines. Other electrical tests will be undertaken when of sufficient importance, provided the

[41] These fees are based on a moderate range of frequency. Tests at extreme frequencies will be subject to a special extra charge, and should always be arranged for in advance of shipment of the apparatus.

[42] This one-half rate applies only to the regular test with five values of primary current; each additional current above five, for the additional transformer, will be charged one-tenth of the base fee as given in the schedules.

[43] When the rated capacity of the transformer exceeds 25 watts, the test at 20 per cent power factor will be made at 12.5 and 25 volt-amperes.

[44] This one-half rate applies only to the regular test with five values of secondary load; each additional secondary load above five, for the additional transformer, will be charged one-tenth of the base fee as given in the schedules.

facilities and time are available. No regular list of fees has been prepared for these miscellaneous tests; fees will be quoted and information furnished upon request. Special tests should always be arranged for in advance of shipment of the apparatus.

It is the desire of the Bureau to cooperate with manufacturers, scientists, and others in bringing about more satisfactory conditions relative to weights, measures, and measuring instruments, and to place at the disposal of those interested such information relative to these subjects as may be in its possession.

All communications should be addressed "Bureau of Standards, Washington, D. C."

6. PUBLICATIONS IN ELECTRICAL MEASUREMENTS.

The following papers embody the results of investigations carried out at this Bureau. They are issued in pamphlet form, and will be sent upon request; they may be ordered by number. This list includes only those papers likely to be of interest to the electrical profession in general. Many other papers are of interest to specialists in various lines. A complete list of the technical publications of the Bureau, with brief abstracts of contents, will be sent upon application.

3. The So-Called International Electrical Units (1904), 38 pp. . . . . *F. A. Wolff.*
18. Wattmeter Methods of Measuring Power Expended upon Condensers and Circuits of Low Power Factor (1905), 15 pp. . . . . *E. B. Rosa.*
21. Influence of Wave Form on the Rate of Integrating Induction Wattmeters (1905), 14 pp. . *E. B. Rosa, M. G. Lloyd,* and *C. E. Reid.*
30. An Efficiency Meter for Electric Incandescent Lamps (1906), 16 pp. . *E. P. Hyde* and *H. B. Brooks.*
33. New Potentiometer for Measurement of Electromotive Force and Current (1906), 14 pp. . *H. B. Brooks.*
48. The Compensated Two-Circuit Electrodynamometer (Nov., 1906), 16 pp. . . . . *E. B. Rosa.*
64. Simultaneous Measurement of the Capacity and Power Factor of Condensers (May, 1907), 61 pp. *F. W. Grover.*
67. Preliminary Specifications for Clark and Weston Standard Cells (Aug., 1907), 18 pp. . . . . *F. A. Wolff* and *C. E. Waters.*
70. Clark and Weston Standard Cells (Sept., 1907), 80 pp. . . . . *F. A. Wolff* and *C. E. Waters.*
73. The Variation of Resistances with Atmospheric Humidity (Oct., 1907), 20 pp. . . . . *E. B. Rosa* and *H. D. Babcock.*
79. A Deflection Potentiometer for Voltmeter Testing (Oct., 1907), 26 pp. . . . . *H. B. Brooks.*
90. Function of a Periodic Variable given by the Steady Reading of an Instrument; with a Note on the Use of the Capillary Electrometer with Alternating Voltages (Dec., 1907), 8 pp. . *Morton G. Lloyd.*
93. Formulæ and Tables for the Calculation of Mutual and Self Inductance (Dec., 1907), 132 pp. *Edward B. Rosa* and *Louis Cohen.*
102. The Principles Involved in the Selection and Definition of the Fundamental Electrical Units to be Proposed for International Adoption (Sept., 1908), 18 pp. . . . . *F. A. Wolff.*
104. The Temperature Formula of the Weston Standard Cell (Sept., 1908), 29 pp. . . . . *F. A. Wolff.*
107. A New Form of Standard Resistance (Oct. 1, 1908), 22 pp. . . . . *Edward B. Rosa.*
113. A Volt Scale for a Watts-per-candle Meter (Feb. 27, 1909), 5 pp. . . . . *Herbert E. Ives.*
116. The Determination of the Ratio of Transformation and of the Phase Relations in Transformers (Feb. 25, 1909) . . . . . *E. B. Rosa* and *M. G. Lloyd.*
119. An Approximate Method for the Analysis of E. M. F. Waves (April 5, 1909) . . . . . *P. G. Agnew.*
124. The Determination of the Constants of Instrument Transformers (July 5, 1909) . . . . . *P. G. Agnew* and *T. T. Fitch.*
129. The Regulation of Potential Transformers and the Magnetizing Current (June 21, 1909) . . *M. G. Lloyd* and *P. G. Agnew.*

All communications should be addressed "Bureau of Standards, Washington, D. C."

S. W. Stratton, *Director.*

Approved:

Ormsby McHarg,

Acting Secretary.